

INTEGRAL CAVITY HYDROGEN MASER

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ABSTRACT

Continuing effort is being directed to developing a thermally, mechanically, and dimensionally stable microwave cavity for a hydrogen maser. The more stable cavity allows for less restricted tuning (or autotuning) of the maser. In addition, overall maser performance is directly related to the stability of the microwave cavity.

This paper presents results of research and development on a new, not previously reported, microwave cavity for the hydrogen maser. The cavity is made of quartz. The storage bulb and the cavity components are bonded together to form an "integral cavity" with no moving parts.

The performance of the integral cavity, installed in a NASA Research (NR) maser, during its three years of continuous operation, is presented. The long-term aging effect of the cavity was evaluated. The cavity frequency drift, after three years of operation, is 0.08 Hz per day, which corresponds to 12.6×10^{-16} per day of the maser frequency drift due to the cavity aging effect.

The atomic line quality factor Q_1 as well as the wall relaxation time t_w were evaluated during the maser operation.

INTRODUCTION

The active hydrogen maser (HM) is one of the atomic oscillators that has attracted much attention because of the spectral properties of its signal. In the field of frequency standards, the HM is unsurpassed for frequency stability. However, this most stable frequency source suffers from low frequency reproducibility. Because of this, the HM is a secondary frequency standard. In applications where spectral purity of the reference signal is important, the HM is the best frequency source available. With the frequency instability of the order 10^{-15} or less, for an integration time longer than 10,000 s, the HM is the only frequency source that provides the required coherence of the reference signal for very long base interferometry. For longer integration time, some systematic effects limit HM frequency stability. The reason for this behavior is unknown, but observations have led to the conclusion that the microwave cavity is the main source of the frequency instability. This conclusion is based on both empirical observations and a theoretical analysis of the quantum oscillator.

The hydrogen maser¹ is a quantum oscillator that operates on the principle of the storage of atoms in the microwave cavity. The hydrogen

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atoms, with proper energy selection, are the source of the energy delivered to the microwave cavity. Part of this energy is used as a reference signal.

Several perturbations affect the stability and spectral purity of the HM signal. Most of them result from technological and material limitations, but all are seen as frequency fluctuations, frequency drift, or inaccuracy of the HM frequency. The most important perturbations of HM frequency are due to cavity pulling, magnetic-field bias, second-order Doppler effect, and wall shift.

A number of papers have been written on the subject of the HM, its performance and its future. A complete review of state-of-the-art hydrogen masers can be found in Ref. 2.

This paper summarizes results of research and development on a new microwave cavity for the NASA Research (NR) hydrogen maser for the NASA Crustal Dynamics Program. Also included with the results will be a description of a unique and, until now, unreported cavity that was designed, fabricated, and installed in the NR maser.

The new temperature and dimensionally stable microwave cavity was the research program goal for an improved hydrogen maser. A cavity made of quartz, with the storage bulb and all the cavity components bonded together, was developed. The "integral cavity" was installed in the NR maser. This NASA Research Experimental (NRX) maser has been in service at APL since November 1983. Substantial improvements in performance have been obtained with the maser. The temperature coefficient of the integral cavity of 1.8 kHz/°C is 18 times lower than that of the NR cavity. The aging factor of the cavity was measured as 0.08 Hz per day in comparison to 0.9 Hz per day for the NR maser. These values correspond to systematic frequency drifts of 12.7×10^{-16} and 140×10^{-16} per day for NRX and NR masers, respectively.

HYDROGEN MASER - CAVITY PULLING

The microwave cavity of the maser and the ensemble of the hydrogen atoms form a coupled electromagnetic system. It is shown that the maser frequency f_m depends on the resonant frequency of the cavity f_c through the following formula:³

$$(1) \quad f_m = f_c + (Q_c/Q_1)(f_c - f_0)$$

where Q_c and Q_1 are the quality factors of the cavity and the atomic line, respectively. The frequency f_0 is the hyperfine frequency of the hydrogen atoms including all systematic frequency shifts. The atomic line quality factor is defined as a ratio of the atomic transition frequency to its half width.

The cavity Q_c is of the order of 40,000 while the atomic line Q_1 is about 2×10^9 in a typical design. Consequently, a microwave cavity

frequency change of 0.071 Hz will result in an HM fractional frequency change of 10^{-15} . The goal for the cavity design is to make it as stable as possible. That includes mechanical, thermal, and dimensional stability. Another important parameter is the thermal coefficient (TC) of the cavity. A cavity made of quartz has a temperature coefficient of the order 1 kHz/°C. A cavity made of aluminum has a TC of about 33 kHz/°C. For these examples, for the HM frequency shift of 10^{-15} , the required temperature stability would be 2.15×10^{-6} and 7.1×10^{-5} °C for cavities made of aluminum and quartz, respectively.

From the above example, it is seen that both the low TC of the cavity and good temperature stability are important for a stable maser. A large thermal mass and good thermal conductivity of the thermal shields surrounding the cavity are considered a proper solution for short- and medium-term stability.

The long-term stability is determined by the stability of the temperature sensors used in the temperature controllers. On the other hand, very low thermal expansion materials like Cervit or ULE⁴ can be used for the cavity. However, the quartz storage bulb inside the microwave cavity drastically changes the thermal performance. Because of the temperature change of the dielectric constant of the storage bulb, a temperature coefficient of the cavity with the storage bulb will exist. Thus, if the lowest possible TC of the cavity is required, one is forced into some kind of cavity compensation, which can easily be done. A temperature coefficient of the cavity/bulb structure of about 100-200 Hz/°C was achieved.

The limit of long-term frequency stability, however, is determined by the dimensional stability of the cavity/storage-bulb structure. Research concerning the stability of a microwave cavity made of quartz and a comparison with the dimensional stability of the same material has been reported.^{6,7}

There is an agreement in the HM community that the cavity should be built with materials of equal thermal and mechanical performance and that its structure should be simple and rigid. This applies to the total structure, the cavity, and the storage bulb. The integral cavity should be made of quartz with solid joints between the elements of the cavity and the storage bulb.⁸ This approach was considered to be the right direction for a highly stable microwave cavity for an NR type maser.

NR MASER

The NR maser⁹ has a specific long cavity where the ratio of length to diameter equals two. In order to accommodate the new cavity in the existing configuration of the vacuum chamber, magnetic shields, electronics, and temperature controllers, it was decided that the aluminum cylinder of the NR maser cavity would be used as a holder and thermal mass for the integral cavity. The standard configuration of an NR maser

cavity is depicted in Fig. 1. Figure 2 shows the conceptual configuration of the cavity for an NRX maser.

INTEGRAL CAVITY

The concept of the integral cavity, with high mechanical and thermal stability, has led to the design depicted in Fig. 3. The cavity cylinder and the endplates are made of quartz. The cavity components and the storage bulb, when bonded together, may be considered to be a simple, uniform structure. The parts of the cavity and the storage bulb were bonded together with a thin film of epoxy (Torr Seal®, a trademark of Varian Assoc.). The cavity cylinder was made from a commercial tube with a 10 in. diameter and a 5 mm wall thickness. The endplates were shaped from commercial flats of 3/8 in. thickness.

The integral cavity has the same type pickup loop as the NR maser except for a small modification because of the difference in thickness of the NR and NRX cavity endplates.

The high electrical conductivity of the cavity was provided by silver coating the external surface of the quartz cylinder and the internal surface of the endplates. The silver-coated surface is indicated in Fig. 3 by broken lines. Before bonding, the silver-coated edges of the quartz cylinder and the surface of the endplates were very carefully polished to provide smooth contact to the endplates. The silver coating was done with silver ink (manufactured by Engelhard, Inc.), which was sprayed on and baked four times to provide the required thickness and a uniform silver surface. With four coats of silver, the unloaded cavity had a quality factor of 48,000.

The endplates of the cavity were shaped to prohibit lateral movement when inserted into the aluminum cylinder. The outside surfaces of the endplates were shaped as in Fig. 4. The edge of the plates had a ring curvature of 1 m, like the holding rings. The holding rings were of anodized aluminum, and the surface was covered with Teflon®. (The technology of filling the porous surface of hard anodized aluminum is known under the trademark Tuftran®). This reduced friction between the quartz cavity and the metal fixture, thus reducing mechanical stresses on the cavity. An additional protection against lateral movement of the cavity was obtained by means of an O-ring, which holds the cavity centered against the aluminum housing.

FABRICATION OF THE CAVITY

The size and shape of the integral cavity were determined by the size and shape of the NR maser. Another restriction was the operating temperature of $50^{\circ} \pm 2^{\circ}\text{C}$. These very strong restrictions had to be met in designing the cavity, which had to have proper resonant frequency at the right temperature and without a tuning element. The low thermal coefficient of the quartz cavity and the well determined size of the cavity have led to the conclusion that the most important item in setting the cavity to the right frequency, during its fabrication, is the weight of the storage bulb. The cavity length correction was an additional option for fine tuning. The fact that the cavity has no tuning element

and has a low temperature coefficient led to very strong requirements on the precision of the cavity dimensions.

In the final stage of cavity tuning, grinding the cylinder to a precise length was the only way to match the frequency, the temperature, and the optimal bulb position.

The optimal bulb position in the microwave cavity is important for its performance under thermal and dimensional change. Another important fact is that a symmetrically centered storage bulb minimizes changes in the hydrogen maser frequency due to gradients of DC and microwave fields along the cavity. This effect is known as the Crampton effect¹⁰.

Figure 5 is an example of how a storage bulb may influence the frequency of the microwave cavity. The solid line represents the cavity frequency change versus bulb vertical position for a high-quality storage bulb. Detuning of the cavity frequency is a function of the weight of the bulb (or its wall thickness), but the symmetry of the curve is a representation of its geometrical and mass distribution symmetry. The dashed line is an example of obtained cavity frequency change for the bulb with nonuniform wall thickness. In this case, no optimal bulb position was found. The solid line in Fig. 5 represents detuning of the cavity by the bulb used in the integral cavity.

For the integral cavity storage bulb, the storage time T_b was chosen to be 1 s. The collimator is made of a quartz tube and is an integral part of the bulb. The purpose of this design is to avoid any potential instability of the cavity frequency due to the aging effect of the traditional rubidium collimator made of Teflon®. The storage bulb with quartz collimator is depicted in Fig. 6. The bulb has a total weight of 375 g and a volume of 4785 cm³.

NRX HYDROGEN MASER

The integral cavity was installed in the NR hydrogen maser in August 1983. Preliminary measurements of the maser performance included measurements of the atomic line quality factor Q_1 , bulb storage time T_b , and static properties of the magnetic shields. Since November 1983, the NRX maser has been in continuous operation and under evaluation. Long-term evaluations of its performance include long-term cavity frequency drift.

Storage Bulb Performance

The storage bulb performance was evaluated by measuring the atomic line quality factor versus the hydrogen pressure. From these data, the bulb storage time T_b (for hydrogen pressure $p_h = 0$) was evaluated.

Figure 7 shows the measured atomic line Q_1 and output power of the hydrogen maser. The hydrogen pressure in Fig. 7 is represented by relative numbers of the dial; however, the dial number for a hydrogen pressure equal to zero is shown. The broken line in Fig. 7 shows the maser output power as a function of hydrogen pressure.

The storage-bulb time constant and the quality of the bulb coating was evaluated on the basis of a known equation, representing the relaxation time of the hydrogen atoms in the storage bulb. A graphic representation of the relaxation times versus hydrogen pressure is depicted in Fig. 8. From this figure, the independence of the hydrogen pressure relaxation time $\gamma_b + \gamma_w$ (the bulb plus the wall relaxation time) is evaluated as 1.1 s. This result indicates that the Teflon® coating is of high quality.

Magnetic Shielding

Because the dynamic magnetic shielding of the NR masers was known, only the static performance of the magnetic shields of the NRX maser was evaluated. A good indication of the shields' performance is a function of the hydrogen maser output power versus the static magnetic field H_0 . Measurements for the NRX maser are shown in Fig. 9. The maser operates without output power degradation at magnetic fields as low as 50 μ G.

LONG-TERM PERFORMANCE OF THE NRX MASER

The main task for the integral cavity was to decrease the aging effect of the cavity and, consequently, lower the aging effect of the hydrogen maser frequency. This is important if one wants to operate a hydrogen maser with limited autotuning. Evaluation of this effect was performed by continuously recording the autotuner of the NRX maser when it was operating in "autotune mode" with reference to another (NR6) hydrogen maser. Examples of obtained data are shown in Fig. 10. Autotuning of the cavity, recorded as numbers on the cavity register from day 311 of 1984 to day 110 of 1986, shows a continuous decline of cavity aging. For the NRX maser, one bit of the cavity register corresponds to a cavity frequency shift of 6.78×10^{-3} Hz. For an operating condition of the maser based on an atomic line $Q_1 = 1.7 \times 10^9$ and a $Q_c = 37,000$, the one bit of the cavity register corresponds to a maser frequency shift of 1.06×10^{-16} . For the observed cavity register numbers depicted in Fig. 10, the systematic frequency shifts are as listed in Table 1. The data show that about two years of operation of the NRX maser were needed in order to reach the maser systematic frequency drift of a few parts $\times 10^{-3}$ per year.

A typical record of the cavity register numbers is depicted in Fig. 11. The 1 to 2 day fluctuations of the cavity register were probably due to very low thermal coupling of the quartz cavity and its temperature-controlled aluminum housing. It was observed that the thermal time constant of the aluminum enclosure is about 1 h, but the time constant of the cavity is about 24 h.

In the existing configuration, the cavity is tuned by temperature, but the heater of the autotuner is attached to its aluminum enclosure and not to the cavity. The time constant of the heat transfer between the enclosure and the cavity does not allow for precise cavity tuning.

Table 1.

Aging Effect of the NRX Maser

Days, Year	Bits/Day	$\Delta f_{\text{cav}}/\text{day}$ (Hz)	$\frac{\Delta f_m}{f_m}/\text{day}(10^{-16})$	$\frac{\Delta f_m}{f_m}/\text{year}(10^{-13})$
311-365, 1984	55	0.37	58.3	21.3
2-44, 1985	56	0.38	59.3	21.6
104-200, 1985	35	0.24	37.1	13.5
2-110, 1986	12	0.081	12.7	4.6

It has to be emphasized that the readings of the cavity register represent not only aging of the microwave cavity but also the frequency change of the microwave cavity due to external influences. It means that the cavity register records required corrections but does not tell why the cavity has changed its frequency. This fact is very important in analyzing aging effects of the hydrogen maser. The reason for cavity frequency changes may be the aging of its structure or it may be, for example, the aging effect of its temperature control systems. There is a pickup loop with a coaxial cable and a front-end amplifier that may affect the microwave cavity. One has to keep in mind that what is measured by reading the cavity register is the aging effect of the whole physics package, not only the cavity. There are insufficient experimental data to determine precisely why different masers have different aging characteristics.

During NRX maser operation, the atomic line Q_1 and the maser's output power were measured.¹¹ Measurements made in September 1983, November 1983, July 1985, and May 1986 are shown in Figs. 12 and 13. The atomic line quality factor Q_1 is continuously increasing during maser operation, but the slope of Q_1 versus hydrogen pressure is decreasing, as can be seen from the data of November 1983, July 1985, and May 1986.

A more detailed analysis, including relaxation times, shows that increasing Q_1 is mainly due to decreasing efficiency of the storage bulb. This may be confirmed by decreasing the maser output power P_0 versus time, as shown in Fig. 13. These effects will be analyzed further.

CONCLUSIONS

The idea of building the microwave cavity for the hydrogen maser with the storage bulb integrated with the cavity structure has two main counter-arguments:

1. The fabrication is more expensive and time consuming than for the standard cavity.
2. There may be situations when the storage bulb might have to be replaced because of deterioration of its performance.

The results presented in this paper give some answers to both of the above counter-arguments. However, before any conclusions are reached, one has to keep in mind that the design and technology reported here are involved in the integral cavity fabrication and already have implied restrictions stemming from the above counter-arguments. These were as follows:

1. To lower the cost, a commercial quartz cylinder without surface finishing was used for the cavity.
2. In order to be able to replace the storage bulb, it was decided that the bonding of the cavity and the storage bulb would be done using epoxy rather than more solid, but more difficult to remove, bonding.

Another strong restriction was to build the integral cavity to fit the existing cavity housing. This was the major time and manpower consuming factor in the process of cavity tuning.

Experience shows that the internal cavity could be built more easily if the cavity cylinder was made of surface-finished quartz and if the silver coating was inside. In this case, even better cavity performance might be expected because there would be no quartz loading. The size of the cavity, with a length-to-diameter ratio of 1:1 instead of 2:1, would ease fabrication.

Operation of the NRX maser during almost three years without a storage bulb or source bulb failure indicates that concern about storage bulb replacement may be substantially lowered. Higher vacuum and material technology than was used in the NRX maser would reduce these concerns even more.

Increasing the atomic line Q_1 versus time may lead to a wrong conclusion that the maser performs better if it operates longer. Unfortunately, the reduced slope of the atomic line Q_1 versus hydrogen pressure as a result of source bulb deterioration leads to declining performance of the autotuning of the hydrogen maser. This effect, noted in reported data, may be a strong argument for another cavity tuning system, one not based on the modulation of the atomic line quality factor.

RECOMMENDATIONS

Further evaluations of the NRX maser are required for a full understanding of its long-term performance. The most important aim is to learn the reason for the observed deterioration in atomic line Q_1 and output power P_0 . The most obvious reason is source bulb contamination, but deterioration of the storage bulb is another possibility. Evalua-

tions of these effects will give much information for future, better performing hydrogen masers.

Another important factor that may greatly improve the meantime frequency stability of this maser is fast cavity tuning. Implementation of varactor tuning to the NRX maser cavity may improve its performance in the medium range of frequency stability.

ACKNOWLEDGMENTS

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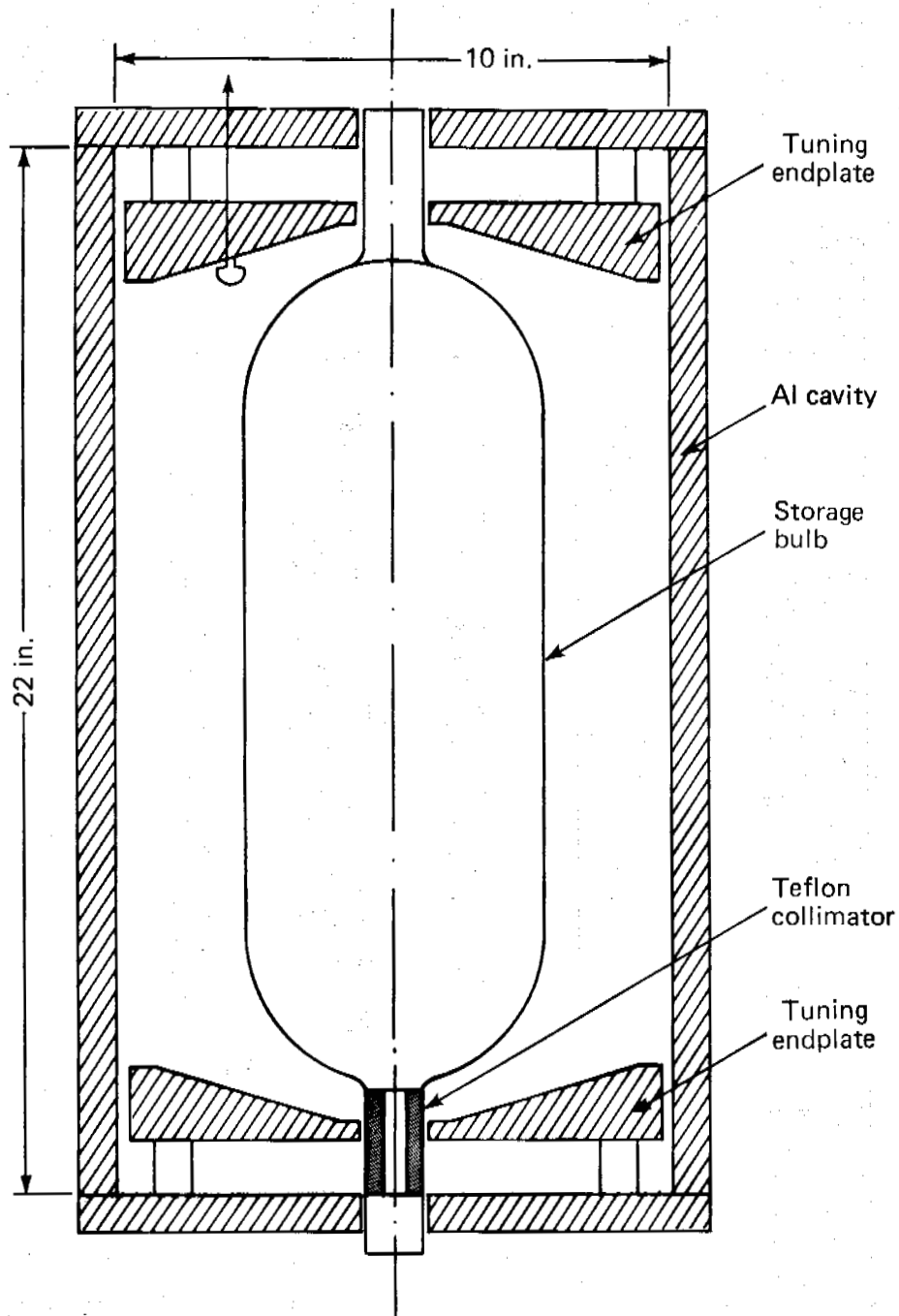


Fig. 1 Microwave cavity of the NR type hydrogen maser.

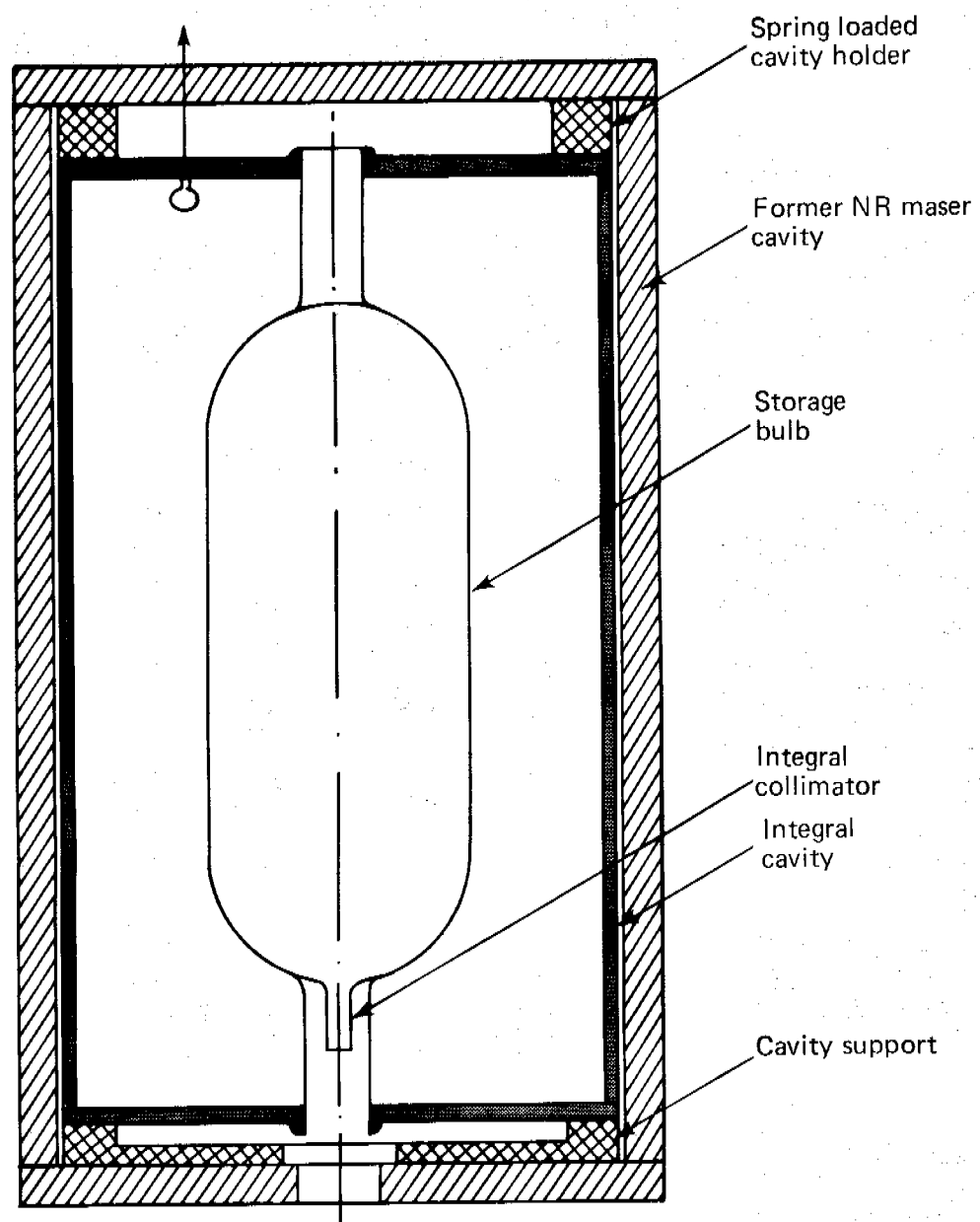


Fig. 2 Configuration of the integral cavity.

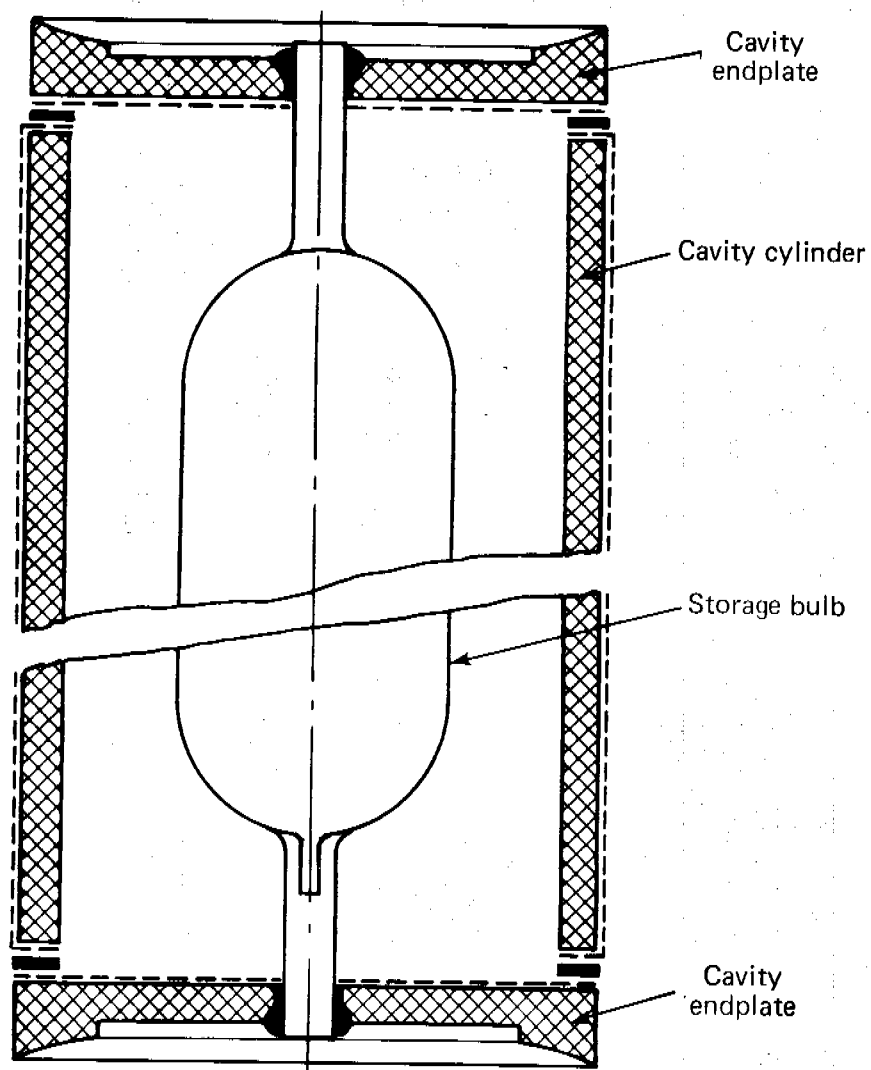


Fig. 3 Integral cavity.

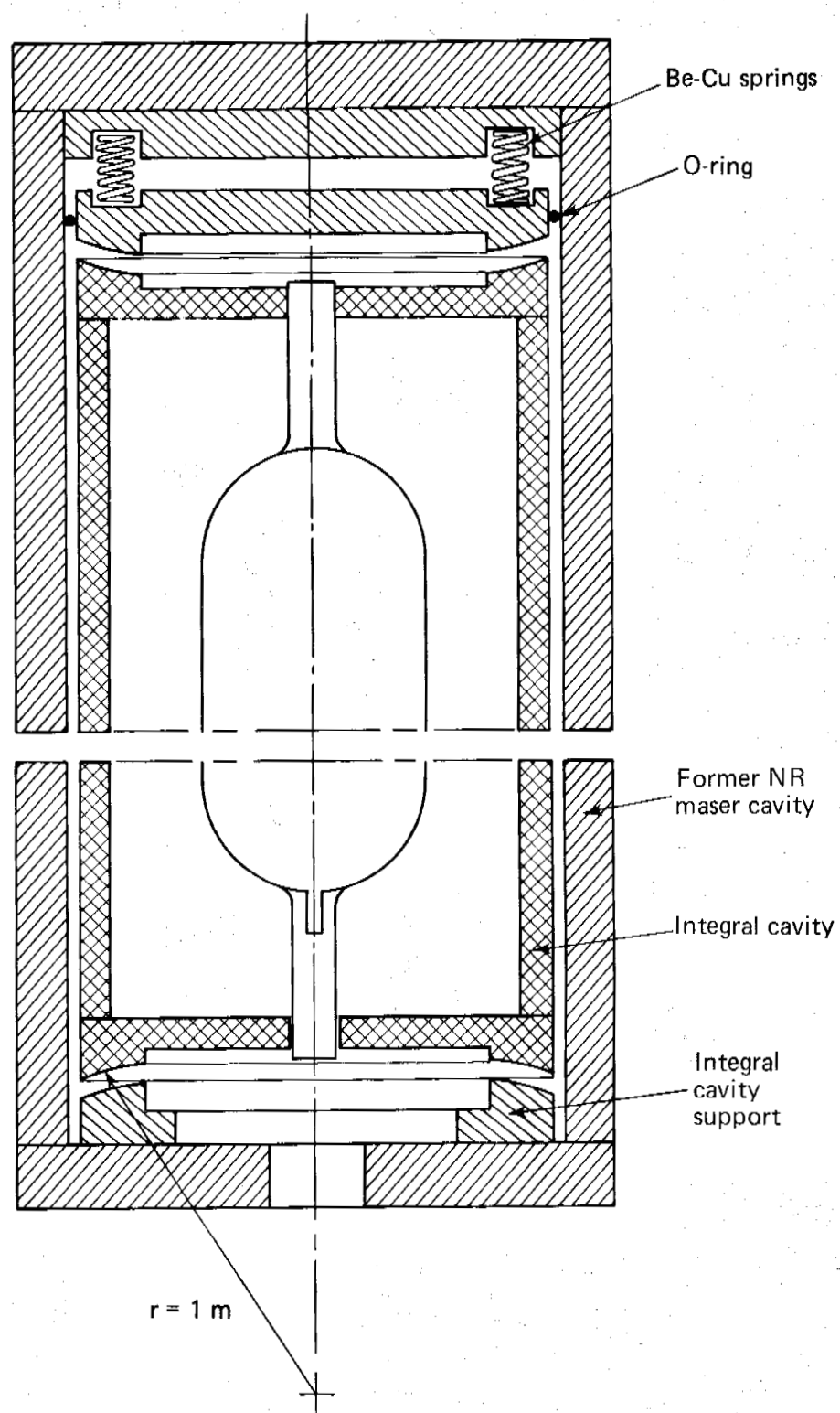


Fig. 4 Housing of the integral cavity.

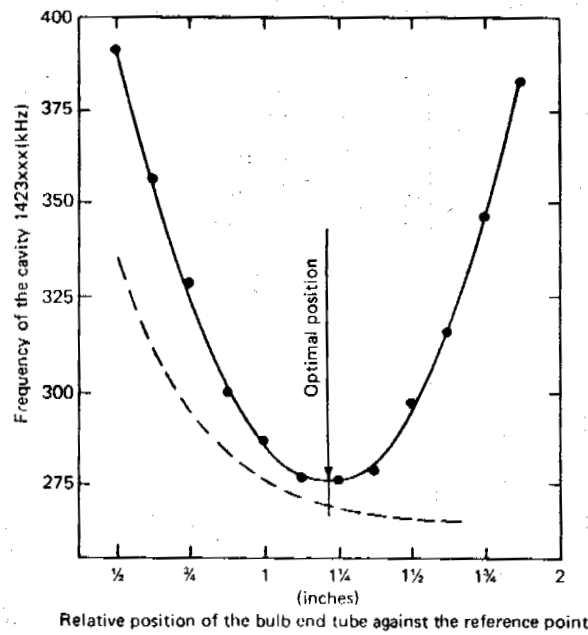


Fig. 5 Frequency of the cavity for the different bulb positions (up and down).

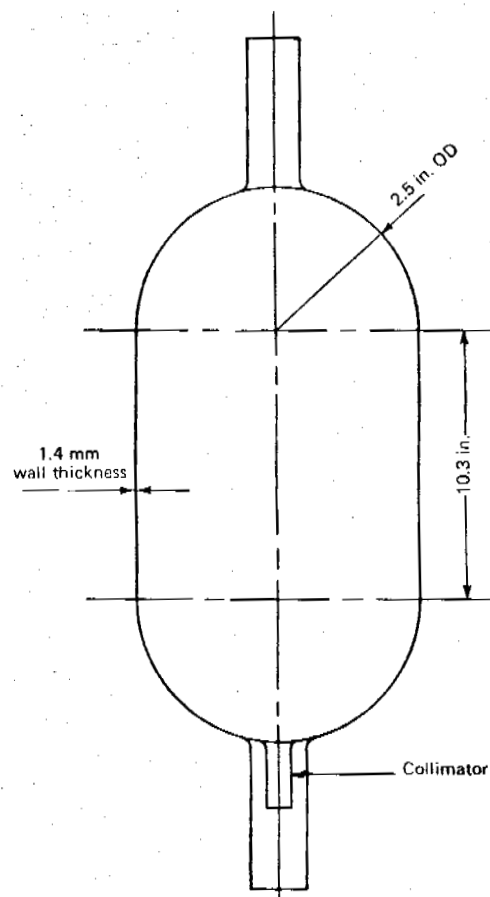


Fig. 6 Storage bulb (not in scale).

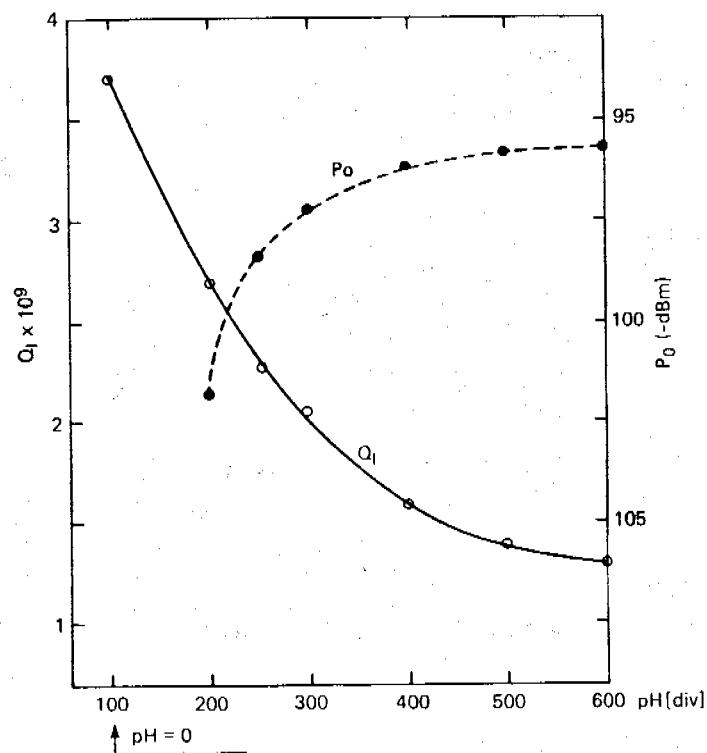


Fig. 7 Atomic line quality factor Q_l , and the output power of NRX maser.

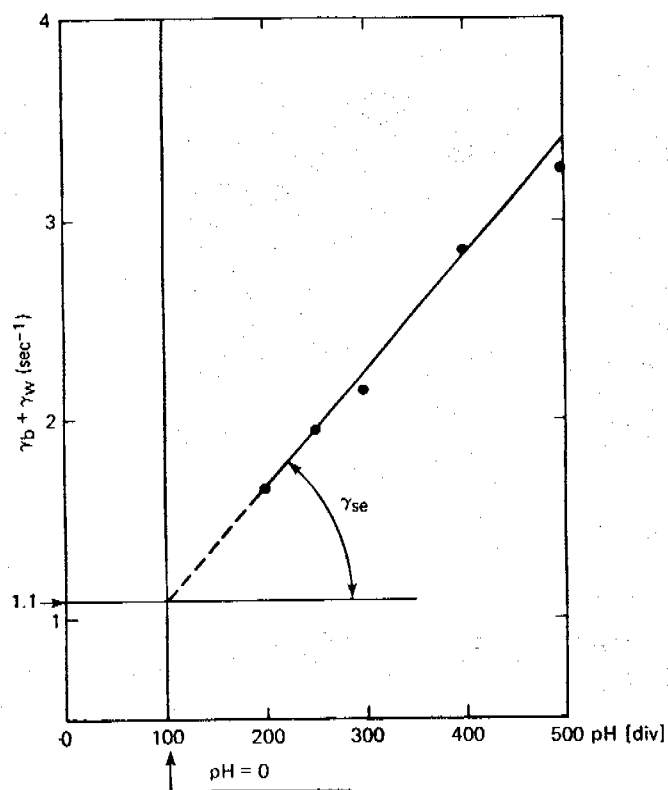


Fig. 8 Relaxation times versus hydrogen pressure.

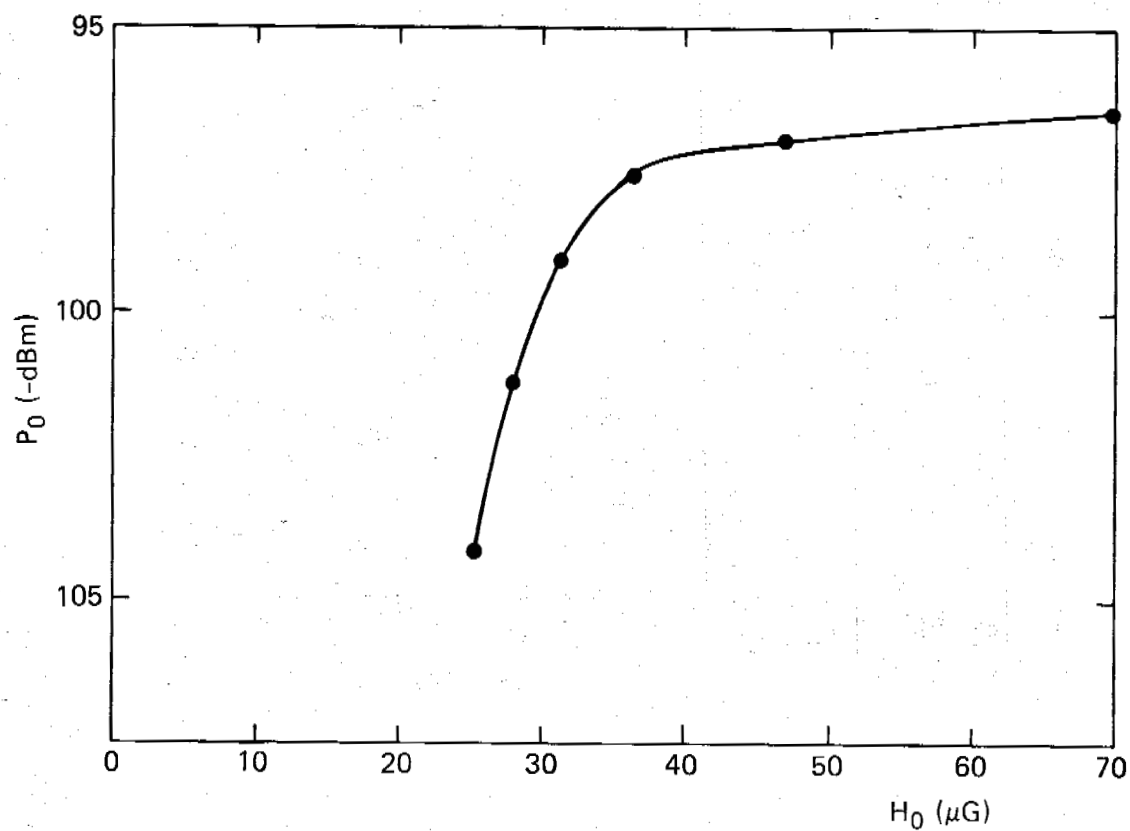


Fig. 9 Output power versus static magnetic field H_0

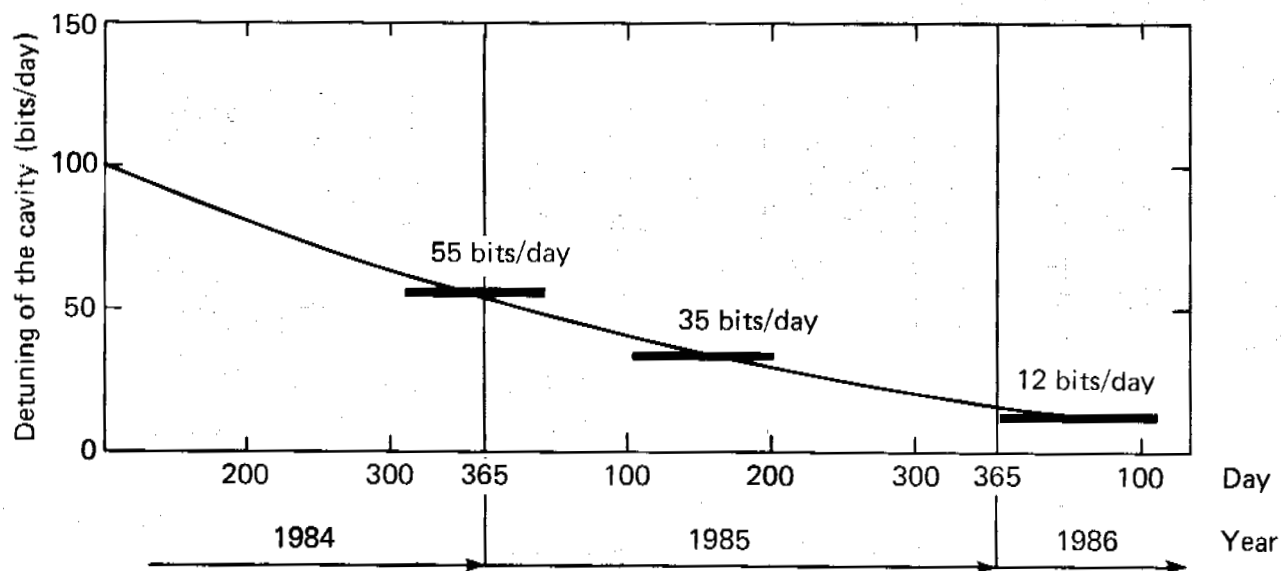


Fig. 10 Long-term aging effect of the NRX maser.

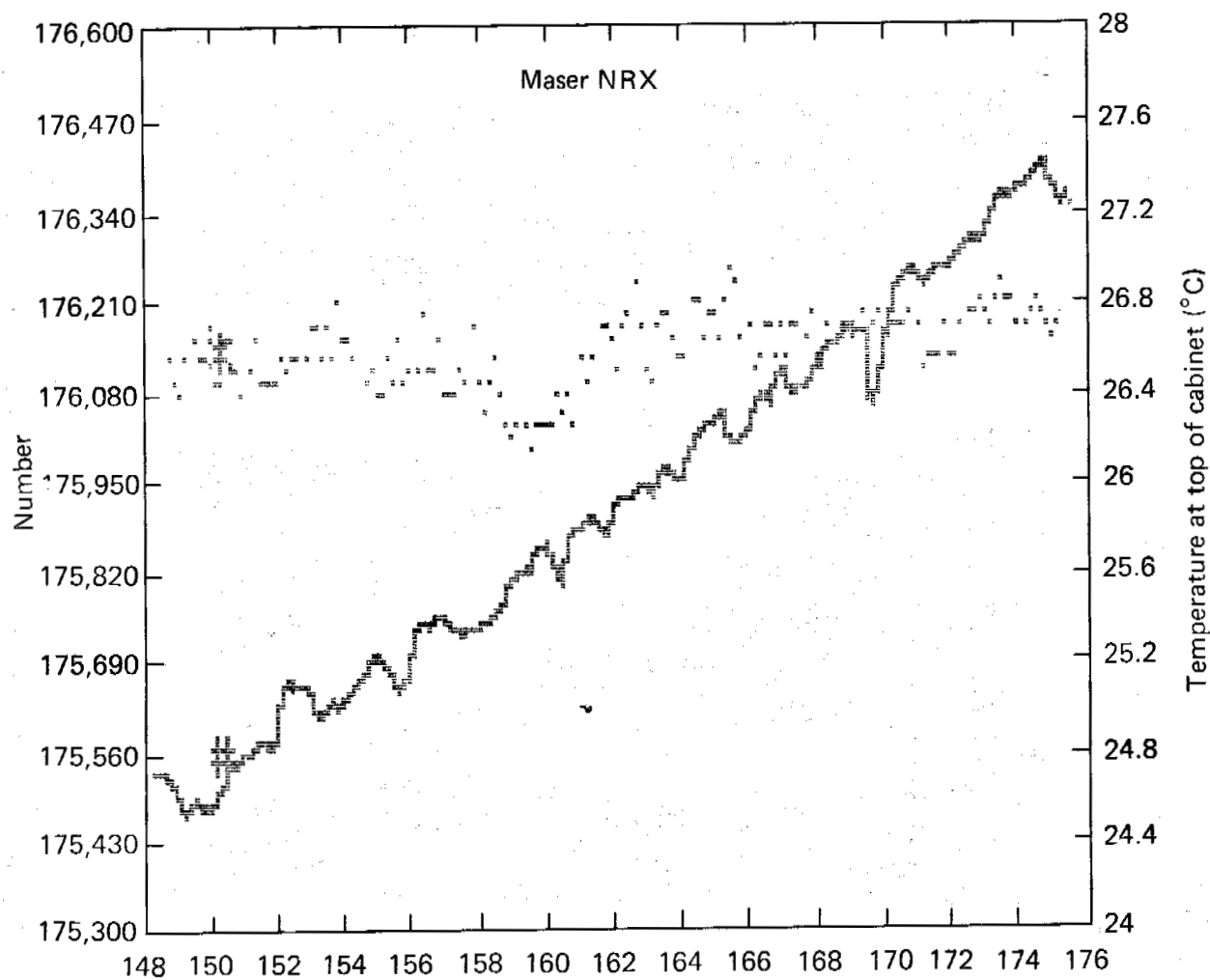


Fig. 11 Short-term aging effect of the NRX maser.

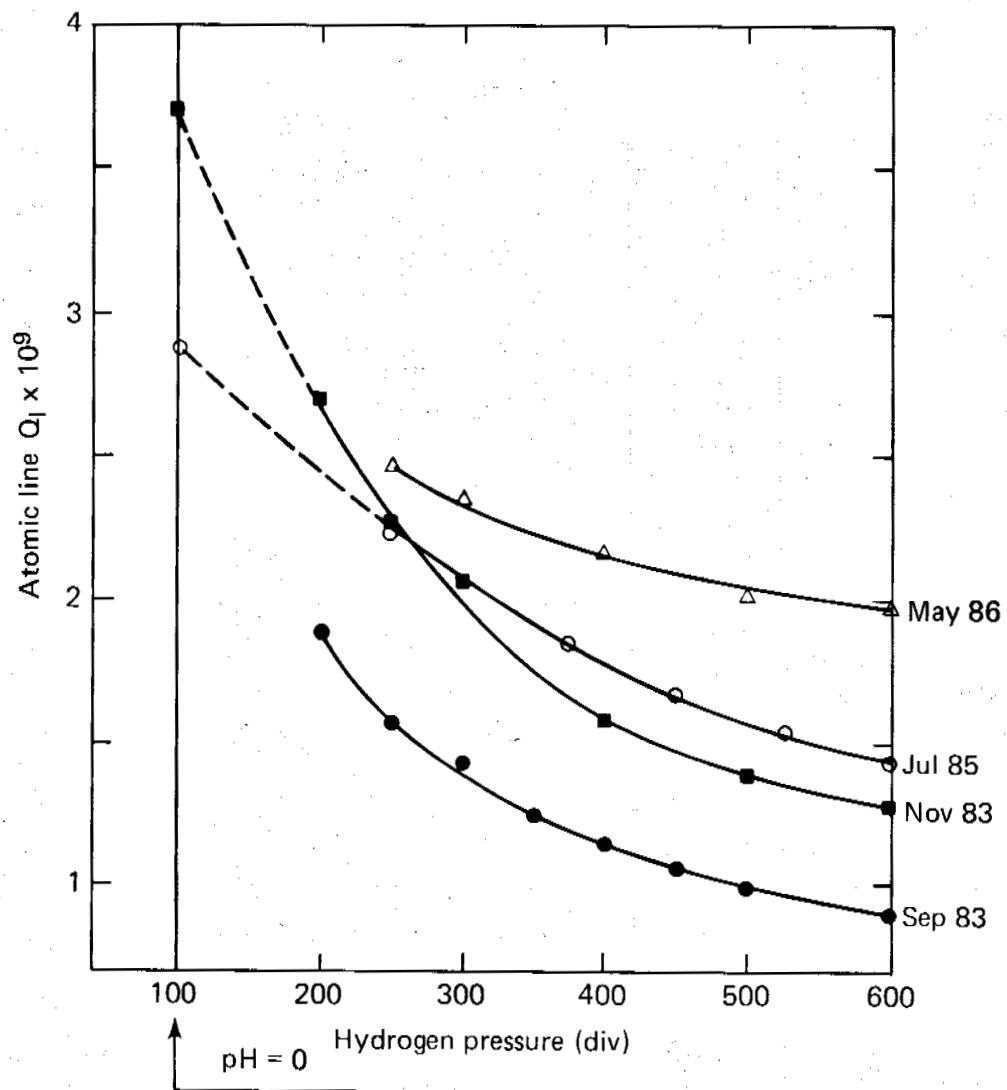


Fig. 12 Atomic line Q_I versus hydrogen pressure .

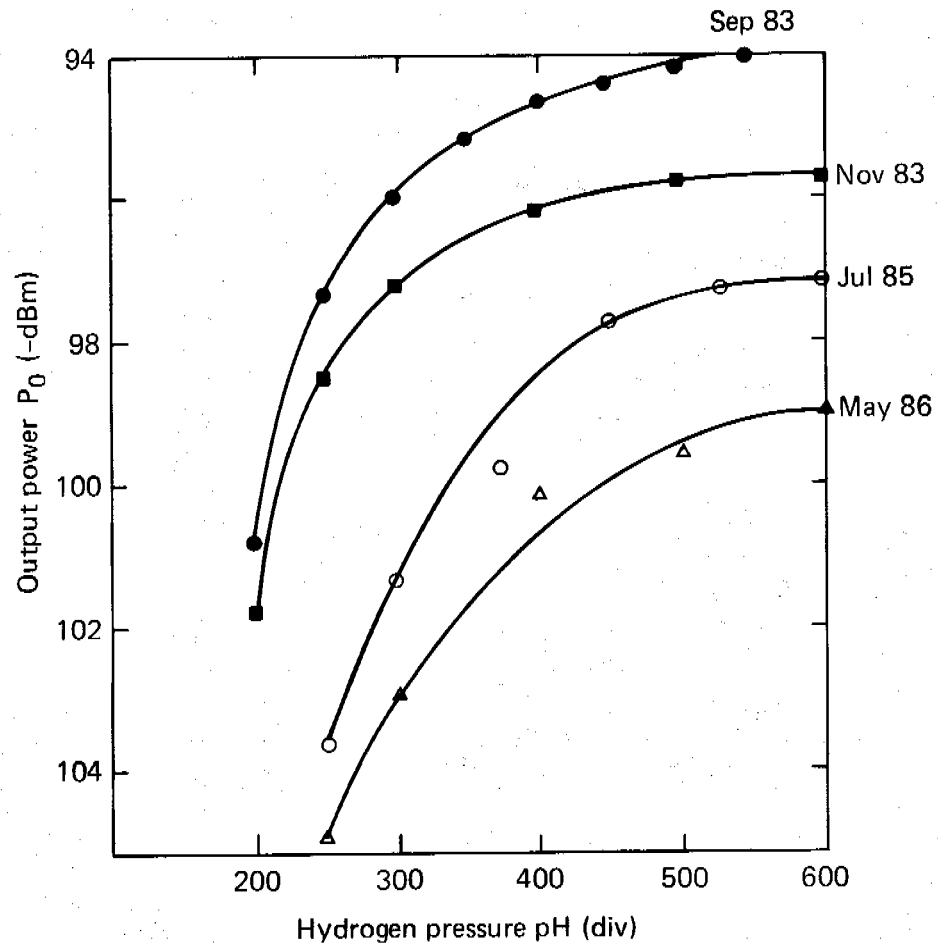


Fig. 13 Output power P_0 of NRX maser versus hydrogen pressure.

QUESTIONS AND ANSWERS

MR. KEN UGLOW, ELECTRONICS RESEARCH: How many loops do you have?

MR. KUNSKI: There is only one loop. There is no tuning loop. Tuning is done by means of the temperature. This is another problem because the time constant between the aluminum housing and the quartz liner is about 24 hours. After you change the temperature, you have to wait 24 hours until the quartz structure stabilizes.

MR. UGLOW: If you had another loop I was going to suggest this scheme for monitoring the cavity change.

MR. KUNSKI: The cavity change was controlled all the time. We can't distinguish between the aging characteristics of the quartz and electronics influence, thermistor aging, wall shift and other things.

GERNOT WINKLER, UNITED STATES NAVAL OBSERVATORY: Would you venture a suggestion as to other means of tuning?

MR. KUNSKI: My favorite method of tuning, which I have never been able to work on, is fast cavity tuning with reference to an external frequency source. I don't see any reason why we have to use spin exchange tuning if we consider that the cavity has to be stable. We can isolate this problem by injecting an external signal as proposed by Audoin, for example. If you refer this servo loop for the cavity tuning to a rubidium frequency standard, the long term stability of the rubidium standard would be adequate for the full lifetime of the maser. Then the cavity would always be at the right frequency. I don't see any reason why you have to influence the physics package so drastically by doing the spin exchange when you only have the cavity to tune. Other fast tuning systems were proposed by John Dick of JPL, where the Q of the cavity was changed. I prefer the other method because it changes the cavity as little as possible.

LAUREN RUEGER, JOHNS HOPKINS: The slope that you see on those charts show bits in the tuning of the device for the cavity. I would like to elaborate on this and show how many parts in $10E-15$ per day the thing is changing. If you have $3 \frac{1}{2}$ bits per day, each bit is worth about 8 parts in $10E17$. Then we are talking about an aging characteristic of about $3.5 E-16$ per day, the auto-tuning is removing that. We think that it is primarily due to the thermistor aging.

MR. KUNSKI: Yes, the thermistor can give you a few millidegrees per year.

MR. RUEGER: We are keeping the temperature to about $1/2$ of a microdegree.

MR. KUNSKI: If you consider the frequency change and use that to calculate the temperature change you get that kind of number, but it is not true that it is stable to a microdegree. (Mr. Kunski showed a chart here.) This chart shows the fluctuations and indicates the time constant of our coupling system and cavity.

VICTOR RHEINHARDT, HUGHES AIRCRAFT: It looks like you have a decay of the source efficiency. Could you show that curve again? It looks like a source

contamination problem or something. Do you have an explanation for that?

MR. KUNSKI: I agree with you. The increasing of the line Q and the decreasing of the output power is due to the source deterioration. The example shows the output power decreasing constantly. I don't have another V_u -graph which shows γ of the bulb plus γ of the wall versus hydrogen pressure. This data was taken when the maser was put together and you see that γ of the bulb plus γ of the wall which contribute to $t_{sub 2}$, the storage time, is a little higher than 1.1 and the storage bulb was designed for one second of $t_{sub 2}$. It means that there is only a little influence of the γ of the wall to the total storage time. So the coating was alright. If you calculate and make this kind of plot from this data, for different line Q 's, you will see that the contribution of γ of the wall is increasing. That makes $t_{sub 2}$ go down. The line Q is still increasing. That means that the source efficiency goes down more rapidly than contamination of the storage bulb. That would be my explanation.

MR. RHEINHARDT: You might be able to reverse that by increasing the RF power.

MR. KUNSKI: Oh, Yes. To restore the bulb we use that procedure.

MR. RHEINHARDT: One other question - did you take any temperature coefficient measurements?

MR. KUNSKI: Do you mean the cavity? Oh, the whole maser - no, we didn't. But, for your information, this maser works in the lab without any thermal chamber and performs much better than the NR type maser in the thermal chamber. The thermal chamber keeps the NR maser to ± 50 millidegrees or less. Lauren says that the thermal stability is a factor of 16 better than the NR.